SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT WE, Akito Kuramata, a citizen of
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Kubota, a citizen of Japan residing at Kawasaki-shi,
Kanagawa, Japan, Kazuhiko Horino, a citizen of Japan
residing at Kawasaki-shi, Kanagawa, Japan and Reiko Soejima,
a citizen of Japan residing at Kawasaki-shi, Kanagawa, Japan
have invented certain new and useful improvements in

OPTICAL SEMICONDUCTOR DEVICE HAVING AN EPITAXIAL
LAYER OF III-V COMPOUND SEMICONDUCTOR MATERIAL
CONTAINING N AS A GROUP V ELEMENT

of which the following is a specification : -

1   TITLE OF THE INVENTION

OPTICAL SEMICONDUCTOR DEVICE HAVING AN
EPITAXIAL LAYER OF III-V COMPOUND SEMICONDUCTOR
MATERIAL CONTAINING N AS A GROUP V ELEMENT

5

BACKGROUND OF THE INVENTION

The present invention generally relates to
optical semiconductor devices and more particularly to
a GaN-family laser diode producing blue to ultraviolet
10   radiation and a fabrication process thereof.

Laser diodes, light-emitting diodes and
photodiodes are optical semiconductor devices used
extensively in the field of optical telecommunication,
optical information processing, recording of
15   information, and the like.

In the case of laser diode, there is a
demand, particularly in the field of optical
information recording, for a laser diode operable in
the optical wavelength band of blue to ultraviolet
20   radiation for increasing the recording density. It
should be noted a laser diode oscillates generally in
the optical wavelength band of red to infrared
radiation. Further, there is a demand for a
photodiode operable in such a short optical wavelength
25   band.

Conventionally, GaN, having a large bandgap,
has been recognized as a promising material for
constructing an optical semiconductor device such as a
laser diode or photodiode that operates in the
30   foregoing blue to ultraviolet wavelength band. A
light-emitting diode using a GaN crystal for the
active layer thereof is already put into practical
use. Further, a laser diode having a double
heterostructure of GaN/InGaN/GaN is already known. By
35   incorporating an appropriate impurity element into the
GaN crystal, it is also possible to cause the laser
diode to oscillate in the visible wavelength band of

green radiation.

It should be noted that GaN has a Wurtzite structure belonging to the hexagonal crystal system, and the preparation of a single crystal substrate of GaN is difficult. Thus, the optical semiconductor devices that use GaN for the active layer have been constructed on the c-surface of a sapphire (Al_2O_3) substrate, which also belongs to the hexagonal crystal system. Thereby, the GaN active layer is grown on the foregoing c-surface of sapphire substrate epitaxially.

FIG.1 shows the construction of a conventional GaN-family laser diode 1 operable in the optical wavelength band of blue to ultraviolet radiation.

Referring to FIG.1, the laser diode 1 is formed on a sapphire substrate 11 and includes a GaN buffer layer 12 formed on the substrate 11, an n-type GaN electrode layer 13 formed on the GaN buffer layer 12, and a lower cladding layer 14 of n-type AlGaN formed on the electrode layer with a composition of $Al_{0.09}Ga_{0.91}N$.

On the lower cladding layer 14, there is formed an optical waveguide layer 15 of n-type GaN, and an active layer having a multiple quantum well (MQW) structure is formed on the n-type optical waveguide layer 15 epitaxially, wherein the MQW structure includes a repetitive stacking of a unit structure of undoped InGaN quantum well layer sandwiched by a pair of undoped GaN barrier layers.

The active layer 15 is covered by an optical waveguide layer 17 of p-type GaN, and an upper cladding layer 18 of p-type AlGaN is formed on the optical waveguide layer 17 with a composition of $Al_{0.09}Ga_{0.91}N$. The upper cladding layer 18 is formed with an optical waveguide ridge 18A extending in the axial direction of the laser diode at a laterally central part thereof, and a contact layer 19 of p-type

1   GaN is formed on the top surface of the optical waveguide ridge 18A.

    The upper cladding layer 18 and the GaN contact layer 19, including both side walls of the

5   optical waveguide ridge 18A, are covered by an insulation film 20 of SiO_2, and a p-side electrode 21 is formed on the insulation film 20 in electrical contact with the GaN contact layer at the optical waveguide ridge 18A via a via-hole formed in the

10   insulation film 20.

    The foregoing semiconductor layers 14 - 18 form together a stacked layered structure defined by two vertical side walls W_1 and W_2 extending substantially vertically to the principal surface of

15   the substrate 11. Further, there is formed an optical cavity in the stacked layered structure by a pair of mirror surfaces disposed so as to face in a direction perpendicularly to the sheet of FIG.1.

    Further, the substrate 11, buffer layer 12

20   and the electrode layer 13 thereon extend laterally beyond the foregoing side wall surface W_2, and an n-side electrode 22 is provided on the electrode layer 13. The laser diode of FIG.1 oscillates in the optical wavelength of 390 - 420 nm and has an

25   important application in the field of high-density information recording.

    The laser diode of FIG.1, however, has a drawback in that, due to the existence of large lattice misfit of as much as 13% or more at the

30   heteroepitaxial interface between the c-surface of the sapphire single crystal substrate 11 and the GaN epitaxial layer 12, the epitaxial layers 15 - 17 forming the MQW structure 16 tend to include various crystal defects with a high concentration level.

35   Further, the laser diode 1 of FIG.1 has a difficulty, contrary to the conventional edge-emission type, in that formation of the electrode on the bottom surface

1   of the sapphire substrate 11 is difficult. Thereby,
the construction, and hence the fabrication process of
the laser diode becomes inevitably complex. In
addition, the sapphire substrate used in the laser

5   diode 1 is difficult to be cleaved, and thus, it is
difficult in the laser diode 1 to form the mirror
surfaces by a conventional cleaving process, contrary
to the conventional edge-emission type laser diode
constructed on a substrate having a zinc blende

10   structure.

In the laser diode 1 of FIG.1, the foregoing
mirror surfaces are formed by a dry etching process,
while such a process of forming the mirror surface by
a dry etching process takes a substantial time.

15   Further, the quality of the mirror surfaces thus
formed is inferior, in terms of flatness and angle, to
the quality of the mirror surfaces formed by a
cleaving process.

It is also proposed to use a conductive SiC

20   substrate, which also belongs to the hexagonal crystal
system, in place of the sapphire substrate and form
the GaN-family active layer of the optical
semiconductor on such an SiC substrate. For example,
the Japanese Laid-Open Patent Publication 10-135576

25   describes a technology of growing a GaN-family active
layer on the (0001)Si surface of a 6H-SiC single
crystal substrate epitaxially. It should be note that
use of an SiC substrate has various advantageous
features such as small lattice misfit, less than 4%,

30   between the GaN active layer and the SiC substrate,
electrical conductivity of the substrate, and
excellent thermal conductivity of the substrate, which
is superior to that of a sapphire substrate. Thus, by
using an SiC substrate, it is possible to construct a

35   laser diode oscillating in the optical wavelength of
blue to violet radiation by using a construction
similar to that of a conventional edge-emission type

1   laser diode.

In order to construct an optical
semiconductor device that uses a GaN-family active
layer formed on such an SiC substrate epitaxially, it
5   is necessary to establish a technology to form a GaN
buffer layer on the SiC substrate epitaxially.
Unfortunately, it is known that an epitaxial growth of
a GaN layer tends to lead to an island-like growth
when the growth is conducted on a SiC substrate. When
10   such an island-like growth occurs in the buffer layer,
it is difficult to form the GaN-family active layer
thereon with a planarized top surface. Further, the
GaN-family active layer thus formed tends to
incorporate therein various crystal defects, while
15   such crystal defects impedes the interaction occurring
in the active layer between GaN and photons. Thereby,
the efficiency of laser oscillation is deteriorated
seriously.

It is known that the problem of island-like
20   growth of GaN film is avoided when the SiC substrate
is covered by a buffer layer of AlN or AlGaN, such
that the desired epitaxial growth of the GaN active
layer occurs on such a buffer layer. However, it has
been not possible to provide electrical conductivity
25   to an AlN film used for the buffer layer.

When a buffer layer of AlGaN is used, on the
other hand, it is possible to provide an n-type
conductivity to the buffer layer, as long as the
content of Al in the AlGaN buffer layer does not
30   exceed 40%. Thus, as long as the composition of the
AlGaN layer is controlled as such, it is possible to
electrically interconnect the GaN active layer with
the SiC substrate via the AlGaN buffer layer.

On the other hand, the condition of forming
35   the conductive AlGaN epitaxial film on a SiC substrate
with a flat and smooth top surface suitable for
forming an active layer of GaN thereon, has not been

1   explored to the date.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present
5   invention to provide a novel and useful optical
semiconductor device and a fabrication process thereof
wherein the foregoing problems are successfully
eliminated.

Another and more specific object of the
10   present invention is to provide an optical
semiconductor device having an SiC substrate and a
nitride layer of a group III element including Ga
formed epitaxially on the substrate, wherein the
epitaxial layer has a flat and smooth top surface and
15   that an excellent electrical interconnection is
secured between the SiC substrate and the nitride
epitaxial layer.

Another object of the present invention is
to provide an optical semiconductor device having a
20   simple structure for confining the electric currents
injected to the laser diode into a desired stripe
region and is simultaneously capable of controlling
the transverse mode oscillation in the state that
laser diode produces a high-power optical output.

25   Another object of the present invention is
to provide an optical semiconductor device having a
selectively grown region of nitride and a fabrication
process thereof.

Another object of the present invention is
30   to provide an optical semiconductor device having a
nitride active layer of a group III element including
Ga and an electron blocking layer provided for
preventing overflowing of electrons from the active
layer, wherein the doping of the electron blocking
35   layer is optimized such that crack formation is
minimized, the carrier confinement in the active layer
is maximized and the threshold voltage of laser

1 oscillation is minimized.

  Another object of the present invention is to provide an optical semiconductor device, comprising:

5 a substrate of SiC having a first conductivity type;

  a buffer layer of AlGaN formed on said substrate epitaxially, said buffer layer having said first conductivity type and a composition represented

10 as $Al_xGa_{1-x}N$;

  a first cladding layer having said first conductivity type, said first cladding layer being formed on said buffer layer epitaxially;

  an active layer formed epitaxially on said

15 first cladding layer;

  a second cladding layer having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;

  a first electrode provided so as to inject

20 first-type carriers having a first polarity into said second cladding layer; and

  a second electrode provided on said substrate so as to inject second-type carriers having a second polarity,

25 said buffer layer containing said first type carriers with a concentration level from $3 \times 10^{18} cm^{-3}$ to $1 \times 10^{20} cm^{-3}$ and said compositional parameter x larger than 0 but smaller than 0.4 ($0 < x < 0.4$).

  According to the present invention, the

30 resistance at the interface between the substrate and the buffer layer is effectively minimized.

  Another object of the present invention is to provide an optical semiconductor device, comprising:

35 a substrate of SiC having a first conductivity type;

  a buffer layer of AlGaN formed on said

1   substrate epitaxially;

        a first cladding layer of AlGaN having said first conductivity type, said first cladding layer being formed on said buffer layer epitaxially;

5   an optical waveguide layer of GaN having said first conductivity type, said optical waveguide layer being formed on said first cladding layer epitaxially;

        an active layer formed epitaxially on said

10   optical waveguide layer, said active layer containing Ga as a group III element and N as a group V element;

        a second cladding layer of AlGaN having a second, opposite conductivity type, said second cladding layer being formed on said active layer

15   epitaxially;

        a first electrode provided so as to inject first-type carriers having a first polarity into said second cladding layer; and

        a second electrode provided on said

20   substrate so as to inject second-type carriers having a second polarity,

        said substrate having a top surface separated from a bottom surface of said active layer by a distance of about 1.6 μm or more.

25   According to the present invention, the threshold current of the optical semiconductor device is successfully minimized.

        Another object of the present invention is to provide an optical semiconductor device,

30   comprising:

        a substrate of SiC having a first conductivity type;

        a first cladding layer having a first conductivity type, said first cladding layer being

35   formed on said substrate epitaxially;

        an active layer formed epitaxially on said first cladding layer;

1   a second cladding layer having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;

      a third cladding layer having said second

5   conductivity type, said third cladding layer being formed on said second cladding layer epitaxially;

      a first electrode provided so as to inject first-type carriers having a first polarity into said second cladding layer; and

10   a second electrode provided on said substrate so as to inject second-type carriers having a second polarity,

      said third cladding layer having a ridge structure,

15   wherein an insulating film is interposed between said second cladding layer and said third cladding layer, said insulating film having an opening in correspondence to said ridge structure, with a width smaller than a width of said ridge structure.

20   According to the present invention, the injection of the drive current is made into an narrowly confined region of the ridge structure, and an efficient control is made on the laser oscillation of the horizontal transverse mode. As a result, the

25   optical semiconductor device shows a smooth operational characteristic free from kink from a low-power state producing a low-power optical beam to a high-power state producing a high-power optical beam.

      Another object of the present invention is

30   to provide an optical semiconductor device, comprising:

      a substrate of SiC having a first conductivity type;

      a first cladding layer having a first

35   conductivity type, said first cladding layer being formed on said substrate epitaxially;

      an active layer formed epitaxially on said

1   first cladding layer;

a second cladding layer having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;

5   a third cladding layer having said second conductivity type, said third cladding layer being formed on said second cladding layer epitaxially;

a contact layer of said second conductivity type, said contact layer being formed on said third

10   cladding layer;

a first electrode provided on said contact layer;

a second electrode provided on said substrate;

15   said third cladding layer forming a ridge structure having a T-shaped cross-section,

said third cladding layer including, at a bottom part thereof, a pair of cuts, such that said cuts penetrate from respective lateral sides of said

20   ridge structure toward a center of said ridge structure.

According to the present invention, the area of the insulation mask used in corresponding to the foregoing cuts when forming the third cladding layer

25   by a selective growth process is effectively minimized, and the formation of particles on the insulation film is minimized accordingly. As the insulation mask itself is removed after the selective growth process and before the step of forming the

30   first electrode, the problem of deterioration of adhesion caused in the first electrode as a result of the existence of the particles is successfully eliminated. As the third cladding layer thus formed has a T-shaped cross-section characterized by a

35   narrowly confined bottom part, the optical semiconductor device of the present invention is capable of injecting drive current selectively into

1   the ridge region.

Another object of the present invention is
to provide a method of fabricating an optical
semiconductor device, comprising the steps of:

5   forming an insulation pattern on a
semiconductor layer such that said insulation pattern
has an opening; and

forming, on said insulation pattern, a
regrowth region of a nitride of Al and a group III

10   element in correspondence to said opening,

said step of forming the regrowth region
being conducted by an metal-organic vapor phase
epitaxy process.

According to the present invention, it

15   becomes possible to form a regrowth region of a
nitride of Al and a group III element on the
insulation mask in correspondence to the opening
formed in the mask by using an MOVPE (metal-organic
vapor phase epitaxy) process. By using halogen

20   together with the gaseous source in the MOVPE process,
the formation of particles on the insulation mask is
minimized.

Another object of the present invention is
to provide an optical semiconductor device,

25   comprising:

a substrate;

a first cladding layer of a nitride of a
group III element formed epitaxially on said
substrate, said first cladding layer having an n-type

30   conductivity;

a first optical waveguide layer of a nitride
of a group III element formed epitaxially on said
first cladding layer, said first optical waveguide
layer having an n-type conductivity;

35   an active layer of a nitride of a group III
element formed epitaxially on said first optical
waveguide layer;

1   an electron blocking layer of a nitride of a group III element formed epitaxially on said active layer, said electron blocking layer having a p-type conductivity;

5   a second optical waveguide layer of a nitride of a group III element formed epitaxially on said electron blocking layer, said second optical waveguide layer having a p-type conductivity;

        a second cladding layer of a nitride of a

10   group III element formed epitaxially on said second optical waveguide layer, said second cladding layer having a p-type conductivity;

        a contact layer of a nitride of a group III element formed epitaxially on said second cladding

15   layer, said contact layer having a p-type conductivity;

        a first electrode provided on said contact layer; and

        a second electrode provided on said

20   substrate;

        each of said electron blocking layer, said second optical waveguide layer and said second cladding layer being doped by Mg;

        wherein said second optical waveguide layer

25   and said second cladding layer contain Mg therein with a concentration level lower than a concentration level of Mg in any of said electron blocking layer and said contact layer.

        According to the present invention, the

30   problem of cracking of the epitaxial layers in the optical semiconductor device is minimized. Further, the drive voltage of the optical semiconductor device is also minimized.

        Another object of the present invention is

35   to provide a semiconductor wafer, comprising:

        an SiC substrate having an n-type conductivity; and

1   an AlGaN layer having an n-type conductivity
formed on said SiC substrate with a composition
represented as $Al_xGa_{1-x}N$,

           wherein said AlGaN layer has a carrier

5   density in the range between $3 \times 10^{18} - 1 \times 10^{20} cm^{-3}$,
and

           wherein said compositional parameter x is
larger than 0 but smaller than 0.4 ($0 < x < 0.4$).

           According to the present invention, the

10   resistance at the interface between the SiC substrate
and the AlGaN buffer layer is minimized.

           Other objects and further features of the
present invention will become apparent from the
following detailed description when read in

15   conjunction with the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

           FIG.1 is a diagram showing the construction
of a conventional GaN-family laser diode;

20   FIGS.2A and 2B are diagrams showing the
experiments constituting one of the basis of the
present invention;

           FIG.3 is another diagram showing the
experiments constituting one of the basis of the

25   present invention;

           FIG.4 is another diagram showing the
experiments constituting one of the basis of the
present invention;

30   FIG.5 is another diagram showing the
experiments constituting one of the basis of the
present invention;

           FIGS.6A and 6B are diagrams showing the
construction of a laser diode according to a first

35   embodiment of the present invention;

           FIG.7 is a diagram showing the experiments
constituting one of the basis of the present

1   invention;

FIG.8 is a diagram showing the construction
of a laser diode according to a second embodiment of
the present invention;

5   FIG.9 is a diagram showing a modification of
the laser diode of FIG.8;

FIGS.10A and 10B are diagrams showing the
fabrication process of a laser diode according to a
third embodiment of the present invention;

10   FIG.11 is a diagram showing a modification
of the laser diode of the third embodiment;p

FIGS.12A and 12B are diagrams showing the
construction of a mask used in a selective growth
process when fabricating the laser diode of the third

15   embodiment and a laser diode of a fourth embodiment of
the present invention;

FIG.13 is a diagram showing the construction
of a laser diode according to the fourth embodiment of
the present invention;

20   FIGS.14A - 14F are diagrams showing the
fabrication process of a laser diode according to a
fifth embodiment of the present invention;

FIG.15 is a diagram showing a distribution
of Mg in a conventional laser diode;

25   FIG.16 is a diagram showing the experiments
constituting one of the basis of the present
invention;

FIG.17 is a diagram showing the experiments
constituting one of the basis of the present

30   invention;

FIG.18 is a diagram showing a Mg
distribution used in a laser diode according to a
sixth embodiment of the present invention;

FIG.19 is a diagram showing a Mg

35   distribution according to a modification of the sixth
embodiment.

1 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT
   [FIRST EMBODIMENT]

        In the description hereinafter, the mixed
   crystal having the composition $Al_xGa_{1-x}N$ (0 < x < 0.4)
5 will be designated merely as AlGaN. When the AlGaN
   mixed crystal has a composition falling in the
   foregoing range (0 < x < 0.4), the doping of AlGaN is
   possible. Further, the AlGaN mixed crystal having
   such a composition can be grown on an SiC substrate
10 with a flat and smooth top surface. The epitaxial
   growth of the AlGaN mixed crystal is typically
   conducted by an MOVPE process, wherein the epitaxial
   layer thus formed shows a flat and smooth top surface
   when the deposition is made under a pressure of 100
15 Torr and the AlGaN mixed crystal contains Al with an
   atomic fraction x of 0.09 or more.

        Thus, it is possible to construct a GaN-
   family laser diode on an n-type SiC substrate covered
   by an n-type $Al_xGa_{1-x}N$ buffer layer, by depositing
20 desired epitaxial layers of GaN or a mixed crystal of
   GaN. The laser diode thus formed typically oscillates
   at the wavelength of 420 nm and has a threshold
   current of about 500 mA. While the laser diode thus
   formed oscillates at the desired blue to ultraviolet
25 wavelength band as is expected, the laser diode also
   has a drawback in that the threshold voltage necessary
   for laser oscillation is very large, as large as about
   22V. In view of the built-in potential of about 3V
   for the pn junction in a GaN crystal, the threshold
30 voltage of the laser diode should be about 4 - 5 V if
   the laser diode is fabricated properly. Thus, the
   foregoing threshold voltage of 22V is deemed
   excessively large for a GaN-family laser diode.

        The inventor of the present invention has
35 conducted a series of experiments on the AlGaN/SiC
   epitaxial system in the investigation forming the
   basis of the present invention, and discovered that

1   the foregoing large threshold voltage arises as a
result of large AlGaN/SiC interface resistance between
the SiC substrate and the AlGaN buffer layer.

In view of the fact that the band structure
5   of SiC and AlGaN is not yet established to the date,
and further in view of the expected existence of
concentration of crystal defects at the interface
between the SiC substrate and the AlGaN buffer layer,
the theoretical approach for reducing the AlGaN/SiC
10   interface resistance is expected to be difficult.
Thus, the present invention explored the solution for
reducing the AlGaN/SiC interface resistance
experimentally.

FIG.2A shows the construction of the sample
15   used in the experiment.

Referring to FIG.2A, a bulk crystal ingot of
Wurtzite-type 6H-SiC, doped by N to the n-type and
grown by an improved Rayleigh process, was used for
forming an SiC substrate 1. More specifically, the
20   SiC substrate 1 was formed from the foregoing 6H-SiC
bulk crystal ingot to have a thickness of about 200
μm, wherein the substrate 1 thus formed was defined by
a principal surface of (0001)Si having a surface area
of about 1 cm^2. The foregoing (0001)Si principal
25   surface of the substrate 1 was then covered by a
buffer layer 2 of n-type AlGaN grown thereon
epitaxially by an MOVPE process with a thickness of
about 1 μm. The AlGaN buffer layer 2 thus formed was
doped by Si to the n-type. The MOVPE process for
30   forming the buffer layer 2 was conducted at the
substrate temperature of 1090°C while using the
gaseous sources of TMG (trimethylgallium), TEG
(triethylgallium), TMA (trimethylaluminum) and ammonia
(NH_3) together with an impurity gaseous source of
35   monosilane (SiH_4).

After the formation of the buffer layer 2, a
contact layer 3 of n-type GaN was grown further on the

1　buffer layer 2 by an MOVPE process with a thickness of
　　about 0.2 μm for reducing the contact resistance.

　　　　After the formation of the contact layer 3,
　　a circular or stripe-shaped electrode 6 was formed on

5　the GaN contact layer for measurement of the AlGaN/SiC
　　interface resistance, more specifically the
　　resistivity, between the substrate 1 and the buffer
　　layer 2, and a Ni electrode 5 was provided on the
　　bottom principal surface of the substrate 1 so as to

10　cover the entirety thereof. It should be noted that
　　the electrode 6 has a stacked structure including a
　　lower layer of Ti and an upper layer of Al, wherein
　　the electrode 6 was formed to have a diameter of 30 -
　　90 μm when the electrode 6 has a circular shape. When

15　the electrode 6 has a stripe structure, the electrode
　　6 was formed of a stripe having a width of 2 - 15 μm
　　and a length of 300 - 900 μm.

　　　　In the experiment, the carrier density was
　　changed variously in the n-type AlGaN buffer layer 2

20　and also in the n-type SiC substrate, in combination
　　with the Al content in the buffer layer 2 and the
　　pressure used in the MOVPE process.

　　　　FIG.2B shows the interface resistivity at
　　the interface between the n-type SiC substrate 1 and

25　the n-type AlGaN buffer layer 2 for the case the
　　carrier density was changed, wherein the horizontal
　　axis of FIG.2B represents the n-type carrier density
　　(cm^{-3}) in the AlGaN buffer layer 2 in a logarithmic
　　scale, while the vertical axis of FIG.2B represents

30　the AlGaN/SiC interface resistivity (Ωcm^2) also in a
　　logarithmic scale. In the experiment of FIG.2B, the
　　carrier density in the SiC substrate 1 was set to 1 x
　　10 $^{17}cm^{-3}$ and the Al content x of the AlGaN buffer
　　layer 2 was set to 0.09 (x = 0.09).

35　　　　Referring to FIG.2B, there are represented
　　the value of the AlGaN/SiC interface resistivity for
　　the structure of FIG.2A in which the carrier density

1   in the n-type AlGaN buffer layer 2 is changed from $1 \times 10^{17} cm^{-3}$ to $1 \times 10^{20} cm^{-3}$. In the construction of FIG.2A, it should be noted that the bulk resistance is negligible for the electrodes 5 and 6, the SiC

5   substrate 1, the AlGaN buffer layer 2 and the GaN contact layer 3. Further, the contact resistance of the electrode, more specifically the interface resistance at the interface between the AlGaN buffer layer 2 and the contact layer 3, is also negligible.

10   Thus, the resistance measured across the electrodes 5 and 6 fairly represents the AlGaN/SiC interface resistance between the SiC substrate 1 and the AlGaN buffer layer 2.

As will be apparent from FIG.2B, the plot of

15   the resistivity reveals the existence of two lines r_1 and r_2. More specifically, the experimental points are aligned on a line r_2 having a gentle gradient in the range of the carrier density larger than about $5 \times 10^{18} cm^{-3}$, while the experimental points are aligned on

20   a more steeper line r_1 when the carrier density is lower than the foregoing value of about $5 \times 10^{18} cm^{-3}$.

It should be noted that the gentle gradient of the line r_2 indicates that the change of the AlGaN/SiC interface resistivity is small when the

25   carrier density is changed. The existence of the two lines, r_1 and r_2, suggests that the physical phenomenon occurring in the range of the line r_1 may be different from the physical phenomenon occurring in the range of the line r_2. From FIG.2B, it will be

30   understood that a low interface resistivity is realized with reliability, by setting the carrier density in the n-type AlGaN buffer layer 2 to be larger than about $5 \times 10^{18} cm^{-3}$.

In a GaN-family laser diode having a mesa

35   structure, the entire resistance of the epitaxial layers generally takes the value of about 10Ω. Thereby, it is desired and necessary that the

1   AlGaN/SiC interface resistance is substantially lower
     than the total resistance of the epitaxial layers.
         In the event each epitaxial layer has a size
     of 700 µm x 4 µm, the AlGaN/SiC interface resistance
5   can be positively reduced to be smaller than the
     resistance of the entire epitaxial layers, even when
     the carrier density in the epitaxial layers is in the
     order of 3 x 10^{18}cm^{-3}. Thus, it is preferable to dope
     the n-type AlGaN layer 2 to have a carrier density of
10   about 3 x 10^{18}cm^{-3} or more, more preferable about 5 x
     10^{18}cm^{-3} or more.
         In doping the n-type AlGaN buffer layer 2,
     it was discovered that there appears a large amount of
     crystal defects on the surface of the AlGaN layer 2
15   when the carrier density in the layer 2 is set larger
     than the value of 1 x 10^{20}cm^{-3}. Due to the excessive
     formation of the crystal defects, experiment for
     measuring the interface resistivity was not possible
     in this case. Thus, it is preferable that the carrier
20   density in the n-type AlGaN buffer layer 2 does not
     exceed the foregoing value of about 1 x 10^{20}cm^{-3}.
         In the foregoing experiments, the carrier
     density of the n-type AlGaN buffer layer 2 on the n-
     type SiC substrate 1 was changed variously, while in
25   the second-series experiments that follow the
     foregoing first-series experiments, the AlGaN/SiC
     interface resistivity was measured while changing the
     carrier density in the n-type SiC substrate 1
     variously. In the second-series experiments, the
30   composition of the n-type AlGaN buffer layer 2 was set
     to have an Al content x of 0.09 (x = 0.09) and the
     carrier density of 5 x 10^{18}cm^{-3}.
         FIG.3 shows the result of measurement of the
     AlGaN/SiC interface resistivity for various carrier
35   densities in the n-type SiC substrate 1 in the range
     from 1 x 10^{17}cm^{-3} to 3 x 10^{19}cm^{-3}, wherein the
     horizontal axis shows the carrier density (cm^{-3})

1   represented in a logarithmic scale, while the vertical
     axis represents the AlGaN/SiC interface resistivity
     (Ωcm) in a logarithmic scale.

        As can be seen clearly from FIG.3, the

5   experimental points are aligned on two lines r_3 and
     r_4. More specifically, the AlGaN/SiC interface
     resistivity is represented by the line r_3 in the range
     of the carrier density smaller than about 1×10^{18}cm^{-3}. In the range of the carrier density larger than

10   about 1×10^{18}cm^{-3}, on the other hand, the AlGaN/SiC
     interface resistivity is represented by the line r_4.

        In the second-series experiments, it was
     discovered that the quality of the SiC bulk crystal is
     deteriorated substantially when the carrier density

15   therein is increased beyond the value of 1×10^{20}cm^{-3}.
     Because of the poor quality of the SiC substrate 1,
     the experiment was not possible in the range of the
     carrier density exceeding the foregoing value of 1×10^{18}cm^{-3}.

20   Summarizing above, it is concluded that the
     n-type SiC substrate 1 preferably has the carrier
     density in the range between about 1×10^{18}cm^{-3} and 1
     $\times 10^{20}$cm^{-3}. When the carrier density is reduced below
     the foregoing value of 1×10^{18}cm^{-3}, the AlGaN/SiC

25   interface resistance increases sharply. When the
     carrier density exceeds the value of 1×10^{18}cm^{-3}, on
     the other hand, the quality of the SiC substrate 1 is
     deteriorated.

        Next, in the third-series experiment, an

30   investigation was made on the effect of the Al content
     x in the n-type AlGaN buffer layer 2 on the AlGaN/SiC
     interface resistance. In the third-series experiment,
     the carrier density in the n-type SiC substrate 1 was
     set to about 1×10^{18}cm^{-3} and the carrier density in

35   the n-type AlGaN buffer layer 2 was set to about 5×10^{18}cm^{-3}.

        FIG.4 shows the AlGaN/SiC interface

1   resistance of the n-type AlGaN buffer layer 2 for the
case in which the Al content x of the buffer layer 2,
represented as $Al_xGa_{1-x}N$, is changed variously,
wherein the horizontal axis represents the

5   compositional parameter x in terms of atomic percent,
while the vertical axis represents the AlGaN/SiC
interface resistivity.

    As can be seen from FIG.4, the experimental
points are aligned on two lines, r_5 and r_6, wherein

10   the AlGaN/SiC interface resistivity is represented by
the line r_5 having a gentle gradient when the
compositional parameter x is smaller than about 9%.
When the compositional parameter x increased beyond
the value of about 9%, on the other hand, the

15   interface resistivity is represented by the line r_6
having a steeper gradient. Further, the interface
resistivity increases with the compositional parameter
x representing the Al content in the AlGaN buffer
layer 2 in any of the lines r_5 and r_6. Thus, from the

20   result of FIG.4, it is preferable that the Al content
x in the n-type AlGaN buffer layer 2 is set smaller
than 9%.

    In the foregoing first through third series
experiments, the formation of the n-type AlGaN buffer

25   layer 2 was conducted by an MOVPE process. On the
other hand, it is believed that a similar result would
be obtained also when the buffer layer 2 is formed by
other deposition process such MBE (molecular beam
epitaxy), as the value of the interface resistivity is

30   primarily controlled by the band structure and the
impurity concentration level.

    Conventionally, the epitaxial growth of a
GaN layer or a mixed crystal layer of GaN has been
conducted by setting the pressure to about 100 Torr

35   when the growth is made by MOVPE. In the foregoing
experiments, the inventor of the present invention has
discovered that it is necessary to increase the Al

1   content x in the n-type AlGaN buffer layer 2, which is
     grown directly on the SiC substrate 1, to be larger
     than 8% in order to obtain a flat and smooth top
     surface. Further, the inventor of the present
5   invention has discovered that a flat and smooth top
     surface can be obtained for the n-type AlGaN buffer
     layer 2 even when the Al content x therein is smaller
     than 8%, by reducing the pressure in the MOVPE
     process.

10   FIG.5 shows the minimum Al content x needed
     for obtaining a planar and smooth top surface for the
     n-type AlGaN buffer layer 2, grown on the n-type SiC
     substrate 1 by the MOVPE process, as a function of the
     pressure used in the MOVPE process. More in detail,
15   the horizontal axis of FIG.5 represents the pressure
     represented in Torr, while the vertical axis
     represents the minimum Al content x in terms of
     percent. In FIG.5, the horizontal axis and the
     vertical axis are represented in a linear scale.

20   Referring to FIG.5, it will be noted that
     the minimum Al content x needed for obtaining a flat
     and smooth top surface for the AlGaN buffer layer 2
     decreases gradually with decreasing pressure used in
     the MOVPE process along a line r_7. In other words,
25   the relationship of FIG.5 represents the fact that the
     desired flat and smooth top surface can be obtained
     for the n-type AlGaN buffer layer 2 even when the Al
     content therein is small, by decreasing the pressure
     in the MOVPE process.

30   In the representation of FIG.5, it should be
     noted that the Al content in the vertical axis may
     contain an error of about ±1%. Thus, the deviation of
     the experimental point for the pressure of 20 Torr
     from the line r_7 may or may not be the result of the
35   error. It should be noted that the experimental
     points for the pressure of 100 Torr, 70 Torr and 50
     Torr are aligned on the line r_7.

1   In the description hereinafter, it is noted
that the value x, indicative of the Al content in the
AlGaN buffer layer 2 and represented in terms of
percent, includes an error of about ±1%.

5   From the result of FIG.5, it is concluded
that the MOVPE process is conducted under a pressure
of about 90 Torr or less when to grow an AlGaN layer
on an SiC substrate with a flat and smooth top surface
and with an Al content of about 8%. In order to grow

10   a similar AlGaN layer with an Al content of about 6%,
on the other hand, it is preferable to conduct the
MOVPE process under a pressure of about 70 Torr or
less. Further, in order to grow a similar AlGaN layer
with an Al content of about 4%, it is preferable to

15   conduct the MOVPE process under a pressure of about 50
Torr or less. In order to grow a similar AlGaN layer
with an Al content of about 2%, it is preferable to
conduct the MOVPE process under a pressure of about 20
Torr or less.

20   In view of the foregoing experimental
results, it is possible to grow an n-type AlGaN buffer
layer on an n-type SiC substrate epitaxially such that
the AlGaN/SiC interface resistance is minimized and
simultaneously the AlGaN buffer layer has a flat and

25   smooth top surface. By growing epitaxial layers on
the SiC substrate thus covered by the buffer layer, it
is possible to form a GaN-family laser diode having a
reduced threshold voltage. As a result of the use of
the SiC substrate, it should be noted that the laser

30   diode includes the n-side electrode formed on the SiC
substrate, similarly to a usual edge-emission type
laser diode.

      FIGS.6A and 6B show the construction of a
GaN-family laser diode 100 based on the foregoing

35   experiments.

      Referring to FIG.6A, the GaN-family laser
diode 100 is constructed on an n-type 6H-SiC substrate

1   31 having a Wurtzite structure and defined by a
     (0001)Si top surface. The substrate 31 is doped by n
     to a carrier density of about $8 \times 10^{17} cm^{-3}$, for
     example.

5   On the foregoing (0001)Si surface of the
     substrate 31, there is provided an n-type epitaxial
     structure 30, and an active layer structure 40 is
     formed on the epitaxial structure 30. Further,
     another epitaxial structure 50 of the p-type is formed

10   on the active layer structure 40.
          It should be noted that the n-type epitaxial
     structure 30 includes a buffer layer 32 of n-type
     AlGaN having a composition of $Al_{0.09}Ga_{0.91}N$ grown
     epitaxially on the (0001)Si surface of the substrate

15   31, another buffer layer 33 of n-type GaN formed
     epitaxially on the buffer layer 32, a cladding layer
     34 of n-type AlGaN having a composition of
     $Al_{0.09}Ga_{0.91}N$ grown epitaxially on the buffer layer
     33, and an optical waveguide layer 35 of n-type GaN

20   grown epitaxially on the cladding layer 34. The
     buffer layer 32 of the n-type AlGaN may have a
     thickness of about 0.15 μm and is doped with Si to an
     impurity concentration level of about $8 \times 10^{18} cm^{-3}$.
     The buffer layer 33, in turn, has a thickness of about

25   0.1 μm and is doped with Si to an impurity
     concentration level of about $3 \times 10^{18} cm^{-3}$. Further,
     the cladding layer 34 of n-type AlGaN has a thickness
     of typically about 0.5 μm and is doped with Si to an
     impurity concentration level of about $3 \times 10^{18} cm^{-3}$.

30   The optical waveguide layer 35 of n-type GaN has a
     thickness of about 0.1 μm and is doped with Si to a
     concentration level of about $3 \times 10^{18} cm^{-3}$.
          The active layer structure 40 forms an MQW
     (multiple quantum well) structure formed of alternate

35   and repetitive stacking of a quantum well layer of
     undoped InGaN having a composition of $In_{0.15}Ga_{0.85}N$
     and a barrier layer of undoped InGaN having a

1   composition of $In_{0.03}Ga_{0.97}N$, wherein the quantum well
       layer typically has a thickness of about 4.0 nm while
       the barrier layer has a thickness of typically about
       5.0 nm. In one example, the quantum well layer is
5   repeated three times and there are provided four
       barrier layers in all in the MQW active layer
       structure 40.

       The p-type epitaxial structure 50 includes
       an electron blocking layer 51 of p-type AlGaN having a
10   composition of $Al_{0.18}Ga_{0.82}N$ grown epitaxially on the
       active layer structure 40, an optical waveguide layer
       52 of p-type GaN formed epitaxially on the electron
       blocking layer 51, a cladding layer 53 of p-type AlGaN
       having a composition of $Al_{0.09}Ga_{0.91}N$ grown
15   epitaxially on the optical waveguide layer 52, and a
       contact layer 54 of p-type GaN grown epitaxially on
       the cladding layer 53. The electron blocking layer 51
       of p-type AlGaN has a large bandgap and blocks the
       electrons overflowing from the active layer structure
20   40 underneath.

       Typically, the electron blocking layer 51
       has a thickness of about 20 nm and is doped with Mg to
       an impurity concentration level of about $5 \times 10^{19} cm^{-3}$.
       The GaN optical waveguide layer 52, in turn, has a
25   thickness of about 0.1 µm and is doped with Mg to an
       impurity concentration level of about $5 \times 10^{19} cm^{-3}$.
       Further, the cladding layer 53 of p-type AlGaN has a
       thickness of typically about 0.5 µm and is doped with
       Mg to an impurity concentration level of about 5 x
30     $10^{19} cm^{-3}$. The contact layer 54 of p-type GaN has a
       thickness of about 0.2 µm and is doped with Mg to a
       concentration level of about $5 \times 10^{19} cm^{-3}$. By
       providing the contact layer 54, the contact resistance
       of a p-side electrode provided thereon is reduced.

35   The foregoing epitaxial layers are grown on
       the SiC substrate 31 by MOVPE under a reduced pressure
       of about 100 Torr. In the MOVPE process, TMG or TEG

1   is used for the gaseous source of Ga, TMA is used for
     the gaseous source of Al, TMI (trimethylindium) is
     used for the gaseous source of In, and NH_3 is used for
     the source of N, together with the dopant gas of SiH_4
5   or biscyclopentadienyl magnesium (Cp_2Mg).

         The n-type SiC substrate 31 may be formed
     from a bulk crystal ingot of n-type SiC grown by an
     improved Rayleigh method that uses a seed crystal.

         It should be noted that the n-type epitaxial
10   structure 30 may be formed by conducting the MOVPE
     process at a substrate temperature of 1090°C with a
     growth rate of about 2 μm/H. On the other hand, the
     MQW structure of the active layer structure 40 may be
     formed by conducting the MOVPE process at a substrate
15   temperature of 780°C with a growth rate of about 0.3
     μm/H. Further, the p-type epitaxial structure 50 may
     be formed by conducting the MOVPE process at a
     substrate temperature of 1130°C with a growth rate of
     about 1 μm/H.

20   In the GaN-family laser diode 100 thus
     obtained, it should be noted that the AlGaN/SiC
     interface resistance at the interface between the n-
     type SiC substrate 31 and the n-type AlGaN buffer
     layer 32 is successfully suppressed in view of the
25   fact that the n-type AlGaN buffer layer 32 having the
     composition of $Al_{0.09}Ga_{0.91}N$ contains the n-type
     carriers with the carrier density of about 8×10^{18}cm^{-3}.
     See the diagram of FIG.2B. It should be noted
     that the thickness of the n-type SiC substrate 31 may
30   be reduced, from an initial thickness of about 200 μm,
     to about 100 μm by polishing the rear surface thereof.

         After the formation of the epitaxial
     structures 30, 40 and 50 on the Si substrate 31, the
     epitaxial structures are subjected to a dry etching
35   process and a mesa structure having a width of 3 - 5
     μm, typically 3.5 μm, is formed to extend in the axial
     direction of the laser diode with a height of about

1   0.4 μm. As a result of the mesa formation, there is
formed a refractive optical guide structure in the
cladding layer 53 wherein the optical guide structure
thus formed controls the transverse mode of laser
5   oscillation.

After the mesa formation, an insulation film
61 of SiO_2 is formed so as to cover the mesa structure
thus formed in the cladding layer 53 and the contact
layer 54, followed by formation of a contact window in
10   the insulation film 61 so as to expose the contact
layer 54. The contact window thus formed may have a
width of 1 - 4 μm.

After the step of formation of the contact
window, an n-side electrode 63 is formed on the SiC
15   substrate 31 by depositing a Ni layer, a Ti layer and
a Au layer consecutively on the bottom surface of the
SiC substrate. Further, a p-side electrode 62 is
formed on the mesa structure by depositing a Ni layer,
a Ti layer and a Au layer consecutively.

20   The structure thus obtained is then
subjected to a cleaving process in the direction
perpendicular to the elongating direction of the mesa
structure, in other words the axial direction of the
laser diode, to form a ridge-type cavity having a
25   length of about 700 μm as represented in FIG.6B. It
should be noted that the ridge-type cavity extends in
the <1Ī00> direction of the SiC substrate 31, while
the cleavage surface has an orientation of [1Ī00]. In
the structure of FIG.6B, mirrors HR are formed on the
30   cleaved surfaces.

It was confirmed that the GaN-family laser
diode 100 thus formed oscillates at the optical
wavelength of 420 nm when driven by a pulse generator
at a frequency of 1 kHz - 10 kHz. Thereby, it was
35   observed that the threshold current is about 500 mA
and the threshold voltage is about 15V.

For the sake of comparison, a laser diode

1   similar to the GaN-family laser diode 100 was
fabricated in which the carrier density of the n-type
AlGaN buffer layer 32 is set to $3 \times 10^{18} cm^{-3}$ while
maintaining the composition of the buffer layer 32 to

5     $Al_{0.09}Ga_{0.91}N$. In this experiment, although it was
confirmed that the laser diode oscillates at the
optical wavelength of 420 nm, the threshold voltage
has increased to 22V. The threshold current remained
the same and took the value of 500 mA. The foregoing

10   result indicates that the threshold voltage of the
laser diode is reduced from 22V to 15V, by increasing
the carrier density in the n-type AlGaN buffer layer
32 having the composition of $Al_{0.09}Ga_{0.91}N$ from $3 \times
10^{18} cm^{-3}$ to $8 \times 10^{18} cm^{-3}$.

15   Further, another experiment was conducted by
fabricating a laser diode similar to the laser diode
100 except that the carrier density in the n-type SiC
substrate 31 is increased from $8 \times 10^{17} cm^{-3}$ to $4 \times
10^{18} cm^{-3}$.

20   It was confirmed that the laser diode thus
formed oscillates at the optical wavelength of 420 nm
similarly to the laser diode 100 and that the
threshold voltage was decreased to 12V, indicating a
further decrease by 3V as compared with the laser

25   diode 100. The threshold current remained the same.

    In view of the relationship of FIG.2B, it is
expected that the threshold voltage may be decreased
further by increasing the carrier density in the n-
type AlGaN buffer layer 32. Further, the relationship

30   of FIG.4 indicates that the AlGaN/SiC interface
resistance, and hence the threshold voltage of the
laser diode, is reduced further by reducing the Al
content in the AlGaN buffer layer 32 below the value
of 0.09.

35   In order to maintain the flat and smooth
surface for the AlGaN buffer layer 32 for the case in
which the Al content is reduced, it is preferable to

1   conduct the MOVPE process for forming the AlGaN buffer
     layer 32 under a reduced pressure environment, in view
     of the relationship of FIG.5. For example, the buffer
     layer 32 may be formed to have a composition

5    $Al_{0.04}Ga_{0.96}N$ in place of the composition of
     $Al_{0.09}Ga_{0.91}N$ by conducting the MOVPE process under
     the pressure of 40 Torr. Other epitaxial layers are
     formed similarly to the case of the laser diode 100.
     When the Si concentration level of 8 x

10   $10^{18}cm^{-3}$ is used in the n-type AlGaN buffer layer 32
     in combination with the foregoing composition of
     $Al_{0.04}Ga_{0.96}N$, it is expected that the threshold
     voltage decreased to about 10V. By further reduction
     of the Al content in the n-type AlGaN buffer layer 32,

15   the AlGaN/SiC interface resistance, and hence the
     threshold voltage, would be reduced further.

     [SECOND EMBODIMENT]
         During the experimental investigation on the

20   GaN-family laser diode 100 described with reference to
     FIGS.6A and 6B, the inventor of the present invention
     has discovered a relationship shown in FIG.7 between
     the threshold current and the thickness of the
     epitaxial layers interposed between the SiC substrate

25   41 and the active layer structure 40, wherein the
     vertical axis represents the threshold current density
     of the laser diode while the horizontal axis
     represents the total thickness of the epitaxial layers
     interposed between the SiC substrate 31 and the active

30   layer structure 40.
         Referring to FIG.7, the threshold current
     generally decreases with increasing thickness in the
     epitaxial layers interposed between the substrate 31
     and the active layer 40 and that the decrease occurs

35   sharply until the total thickness of the epitaxial
     layers reach the value of about 1.6 μm.
         While the reason of this phenomenon is not

1   clearly understood, it is probable that the defect
     density in the epitaxial layers decreases with
     increasing total thickness of the epitaxial layers
     between the substrate 31 and the active layer
5   structure 40.

     Thus, in view of the relationship of FIG.7,
     it is concluded that the threshold current of the
     laser diode can be reduced by increasing the total
     thickness of the epitaxial layers interposed between
10   the substrate 31 and the active layer structure 40.
     On the other hand, there arises a problem of cracking
     in the epitaxial structure 30, 40 or 50 when the
     foregoing total thickness is increased excessively,
     probably due to the tensile stress caused as a result
15   of the difference in thermal expansion between the SiC
     substrate 31 and the nitride epitaxial layers thereon.

     The inventor of the present invention has
     discovered that the cracking of the epitaxial
     structures is effectively suppressed by setting the Al
20   content y of the lower cladding layer 34 of n-type
     AlGaN having a composition represented as $Al_yGa_{1-y}N$,
     to be smaller than the Al content x of the foregoing
     n-type AlGaN buffer layer 32, of which composition is
     represented as $Al_xGa_{1-x}N$ (y < x). Further, the
25   inventor of the present invention has discovered that
     the problem of cracking of the epitaxial layers is
     further suppressed by setting the Al content z of the
     upper cladding layer 53 of p-type AlGaN having a
     composition represented as $Al_zGa_{1-z}N$, to be smaller
30   than the Al content y in the lower cladding layer 34
     (z < y). It is believed that the foregoing
     suppression of the crack formation in the epitaxial
     layers is achieved as a result of cancellation of the
     tensile stress, which is induced in the epitaxial
35   layer by the differential thermal expansion of the SiC
     substrate 31 and the epitaxial layers, by a
     compressive stress. It should be noted that the

1   foregoing compressive stress is induced in the
     epitaxial layers including the buffer layer 32 and the
     cladding layers 34 and 53 as a result of the
     difference in the lattice constant between the SiC
5   substrate 31 and the epitaxial layers thereon.

         FIG.8 shows the construction of a laser
     diode 200 according to a second embodiment of the
     present invention, wherein those parts corresponding
     to the part described previously are designated by the
10   same reference numerals and the description thereof
     will be omitted.

         Referring to FIG.8, the laser diode 200 has
     a construction in which the GaN buffer layer 33 is
     omitted, and the AlGaN buffer layer 32, the AlGaN
15   cladding layer 34 and the GaN optical waveguide layer
     35 are formed to have respective thicknesses of 1.0
     μm, 1.5 μm and 0.1 μm. As a result, the total
     thickness of the epitaxial layers interposed between
     the SiC substrate 31 and the active layer structure 40
20   takes a value of 2.6 μm, and the threshold current
     density of laser oscillation 200 is reduced to about 7
     - 8 kA/cm^2.

         In the present embodiment, it should be
     noted that the lower cladding layer 34 of n-type AlGaN
25   contains Al with an atomic fraction y of 0.10 (y =
     0.10), while this value of the Al content y is smaller
     than the Al content x of 0.15 (x = 0.15) of the n-type
     AlGaN buffer layer 32. Further, it should be noted
     that the upper cladding layer 53 of p-type AlGaN
30   contains Al with an atomic fraction z of 0.08 (z =
     0.08), while this value z of the Al content of the
     upper cladding layer 53 is smaller than the foregoing
     value y for the lower cladding layer 34.

         As a result of the foregoing construction,
35   the laser diode 200 of the present embodiment
     successfully eliminates the crack formation in the
     epitaxial layers.

1   Other features of the present embodiment are
substantially the same as those of the laser diode 100
described previously and further description thereof
will be omitted.

5   FIG.9 shows the construction of a laser
diode 210 corresponding to a modification of the laser
diode 210 of the present embodiment, wherein those
parts corresponding to the parts described previously
are designated by the same reference numerals and the
10   description thereof will be omitted.

In the present modification, the buffer
layer 32, the cladding layer 34 and the optical
waveguide layer 35 are formed to have respective
thicknesses of 0.35 μm, 1.15 μm and 0.1 μm, thus
15   leading to the total thickness of 1.6 μm for the
epitaxial layers interposed between the SiC substrate
31 and the active layer structure 40. In the present
modification, the buffer layer 32 and the lower
cladding layer 34 are formed to have the same Al
20   content of 0.10 for the compositional parameters x and
y, while the upper cladding layer 53 contains Al with
a reduced content of 0.08 for the compositional
parameter z. Thereby, the problem of cracking of the
epitaxial layers is suppressed effectively also in the
25   present modification.

[THIRD EMBODIMENT]

In the ridge-type laser diode 100, 200 or
210 described before, the control of transversal mode
30   laser oscillation in the active layer structure 40 is
achieved by forming a mesa structure in the upper
cladding layer 53 as explained before.

In the ridge-type laser diode having such a
structure, it is necessary to form the mesa structure
35   to have a width of less than about 2 μm in order to
achieve a satisfactory control of the transversal mode
oscillation, while the formation of such a narrow mesa

1   structure has been difficult. Further, the foregoing conventional ridge-type laser diode has a drawback in that the contact area between the electrode 62 and the contact layer 54 is reduced inevitably when the width

5   of the mesa structure is thus reduced below 2 μm. It should be noted that the width of the contact window formed in the SiO_2 film 61 is reduced together with the width of the mesa structure, while formation of such a very small contact window in the SiO_2 film 61

10   on the mesa structure raises various problems.

       Further, the ridge-type laser diodes have a further drawback in that the confinement of the optical radiation inside the active layer structure 40 in the vertical direction tends to become weak and

15   insufficient. In order to realize a satisfactorily strong optical confinement in the active layer structure 40, it is necessary to increase the thickness of the upper cladding layer 53 further, while such an increase of thickness of the upper

20   cladding layer 53 tends to cause a cracking therein. It should be noted that the cladding layer 53 has a lattice constant different from that of the buffer layer 32. In view of insufficient optical confinement in the active layer structure 40, the ridge-type laser

25   diodes including the laser diodes 100, 200 and 210 tend to show the problem of optical loss caused by the electrode 62 or poor far-field pattern (FFP) in the optical beam produced by the laser diode.

       FIGS.10A and 10B show a fabrication process

30   of a laser diode 300 wherein the foregoing problems are eliminated, wherein those parts corresponding to the parts described previously are designated by the same reference numerals and the description thereof will be omitted.

35   Referring to FIG.10A, the laser diode 300 is constructed on the n-type SiC substrate 31 carrying thereon the n-type epitaxial structure 30, the active

1   layer structure 40 and the p-type epitaxial structure
     50 similarly to the laser diodes of the previous
     embodiments, wherein the mesa formation in the upper
     cladding layer 53 or the contact layer 54 forming a
5   part of the p-type epitaxial structure 50 is omitted.
     It should be noted that the n-type epitaxial structure
     30 includes the n-type nitride layers 32 - 35 while
     the p-type epitaxial structure includes the p-type
     nitride layers 51 - 54 similarly as before. As a
10   result, the contact layer 54 has a flat top surface
     and an insulation film 301 of SiO_2 is formed on the
     flat top surface of the contact layer 54 by a high-
     temperature CVD process with a thickness of about 300
     nm.

15   The SiO_2 film 301 is then patterned by a
     photolithographic process using HF as an etchant to
     form a stripe opening 301W in the SiO_2 film 301 with a
     width of about 1 μm, wherein the stripe opening 301W
     is formed so as to extend in the axial direction of
20   the laser diode 300 coincident with the <1Ī00>
     direction of the SiC substrate 31.

          Next, in the step of FIG.10B, the deposition
     of a p-type AlGaN layer having a composition of
     $Al_{0.09}GA_{0.91}N$ is made on the exposed part of the GaN
25   cap layer 54 exposed at the foregoing stripe opening
     301W by an MOVPE process while using the SiO_2 film 301
     as a mask, to form a third cladding layer 302 with a
     thickness of about 1.4 μm. It should be noted that
     the MOVPE process is conducted under a condition
30   similar to the condition used for forming the
     epitaxial layers in the p-type epitaxial structure 50.
     The third cladding layer 302 thus grow not only in the
     upward direction but also in lateral directions to
     form a ridge structure covering the insulation film
35   301 and extending thereon in the axial direction of
     the laser diode.

          Next, in the step of FIG.10B, a contact

1   layer 303 of p-type GaN is formed on the third
     cladding layer 302 by an MOVPE process with a
     thickness of about 0.2 μm so as to cover both side
     walls and a top surface thereof continuously, and the
5   electrode 62 is deposited so as to cover the contact
     layer 303 continuously over a part corresponding to
     the side walls and the top surface of the underlying
     third cladding layer 302. Further, the bottom surface
     of the n-type SiC substrate 31 is polished and the
10   electrode 63 is formed on the bottom surface of the
     SiC substrate 31 thus polished, similarly to the
     embodiments described before.

          According to the laser diode 300 of the
     present embodiment, the photolithographic patterning
15   process of the insulation film 301 is conducted in the
     step of FIG.10A on the flat, planar principal surface
     of the GaN cap layer 54. Thereby, the patterning
     process is under an ideal condition with an excellent
     precision and the stripe opening 301W is formed
20   relatively easily to have a width of less than 1 μm.

          In the present embodiment, it should be
     noted that the cap layer 54 of GaN is provided for
     preventing the oxidation of the AlGaN cladding layer
     53 when forming the insulation film 301. The
25   insulation film 301 is by no means limited to SiO_2 but
     other materials such as SiN or Al_2O_3 may also be used.

          It should be noted that the structure of the
     present embodiment is applicable also to the
     conventional laser diode constructed on a sapphire
30   substrate such as the one described with reference to
     FIG.1. When using a sapphire substrate, the stripe
     opening 301W is formed in the insulation film 301 so
     as to extend in the <11Z0> direction of the sapphire
     substrate corresponding to the <1Ī> direction of a GaN
35   crystal.

          According to the laser diode 300 of the
     present embodiment, in which the electrode 62 covers

1   the top surface and both side walls of the third
cladding layer 302 continuously via the contact layer
303, the contact resistance of the electrode 62 is
reduced substantially. Further, in view of the fact

5   that the injection of carriers (holes) into the active
layer structure 40 is restricted to the foregoing
elongating stripe opening 301W, the desired current
confinement in the active layer structure 40 is
achieved effectively without restricting the width of

10   the cladding layer 302 strictly. Thereby, an
effective control of the transverse mode becomes
possible.

     As the cladding layer 302 is formed as a
result of the selective growth of the AlGaN layer

15   occurring in the narrowly confined stripe opening
301W, there occurs no substantial problem of
relaxation of crystal lattice in the AlGaN cladding
layer 302 and the crack formation does not occur in
the cladding layer 302 even when the third cladding

20   layer 302 is formed to have an increased thickness.
Thereby, an excellent optical confinement is realized
in the vertical direction and the far-field pattern of
the laser diode is improved substantially. Further,
the problem of optical loss caused by the electrode 62

25   is also reduced.

     In the step of FIG.10B, there may be a case
in which particles are formed on the insulation film
301 during the process of forming the cladding layer
302 or the contact layer 303 by the selective growth

30   process. It should be noted that the insulation film
301 is used in the foregoing selective growth process
as a mask. When there occurs such a deposition of
particles on the insulation film 301, the adherence of
the electrode 62 may be deteriorated.

35   In order to avoid the foregoing risk of
deterioration of adherence of the electrode 62, the
SiO_2 film 301 may be removed by a wet etching process

1   after the formation of the cladding layer 301 and the
    contact layer 303 by using a suitable etchant such as
    HF. As a result of removal of the SiO_2 film 301, the
    particles deposited thereon are also removed.

5   FIG.11 shows the construction of a laser
    diode 310 thus formed according to a modification of
    the present embodiment.

        Referring to FIG.11, the third cladding
    layer 302 has a T-shaped form having a reduced width

10 at the bottom part thereof similarly to the structure
    of FIG.10B, wherein it should be noted that the SiO_2
    film 301 of FIG.10B is replaced with an air gap 301G
    cutting into the cladding layer 302 from both lateral
    sides thereof at the bottom part of the cladding layer

15 302. Further, an SiO_2 film similar to the SiO_2 film
    61 is provided so as to cover the top surface and both
    side walls of the cladding layer 302 wherein the SiO_2
    film 61 covers the exposed top surface of the contact
    layer 54. The contact laser 61 is formed with an

20 opening exposing the GaN contact layer 303 covering
    the top surface of the third cladding layer 302 and
    the electrode 62 makes an ohmic contact with the
    exposed top surface of the third cladding layer 302.

        Typically, the SiO_2 film 61 is formed by a

25 vapor phase deposition process such as a high-
    temperature CVD process and may penetrate into the air
    gap 301G. Thereby, the air gap 301G may be filled
    entirely or partially by SiO_2 forming the SiO_2 film
    61.

30   In the laser diode 300 or 310 of the present
    embodiment, it is possible to eliminate the contact
    layer 303.

    [FOURTH EMBODIMENT]

35   FIG.12A is a plan view showing the
    insulation film 301 used as a mask in the foregoing
    fabrication process of the laser diode 300 or 310,

1   when forming the cladding layer 302 or 303 by a
       selective growth process.

            Referring to FIG.12A, the insulation film
       301 includes a number of linearly extending stripe
5   openings each having a width of about 1 μm. The
       stripe openings are repeated with an interval of about
       300 μm, and thus, there is formed a wide area of SiO_2
       between one stripe opening and an adjacent stripe
       opening.

10   Thus, it will be easily understood that
       there occur an extensive formation of particles on the
       mask when the insulation film 301 of FIG.12A is used
       for the mask during the MOVPE process for forming the
       third cladding layer 302 or the contact layer 303.

15   In the present embodiment, the foregoing
       problem of deposition of particles on the mask is
       eliminated by using a mask 301A shown in FIG.12B.

            Referring to FIG.12B, it will be noted that
       a pair of linearly extending insulation stripes 301a
20   and 301b each having a width of 6 μm are disposed
       adjacent with each other to form a mask pattern 301c,
       with a gap 301n of about 1 μm formed between the
       insulation stripes 301a and 301b forming the mask
       pattern 301c, wherein the foregoing mask pattern 301c
25   thus formed is repeated a number of times with a pitch
       of 300 μm. In the mask 301A thus including the
       repetition of the mask patterns 301c, it should be
       noted that the underlying GaN contact layer 54 is
       exposed between a mask pattern 301c and an adjacent
30   mask pattern 301c, and the problem of particle
       formation is effectively eliminated. Instead of
       forming particles, the source elements supplied during
       the MOVPE process for forming the p-type AlGaN
       cladding layer 302 or the p-type GaN contact layer 303
35   form an epitaxial layer of p-type AlGaN or p-type GaN
       on the exposed surface of the GaN contact layer 54.

            FIG.13 shows the construction of a laser

1   diode 400 that uses the mask 301A of FIG.12B for the
selective growth process of the third cladding layer
302 and the contact layer 303 according to a fourth
embodiment of the present invention, wherein those
5   parts corresponding to the parts described previously
are designated by the same reference numerals and the
description thereof will be omitted.

     Referring to FIG.13, the mask 301A is formed
on the contact layer 54 of p-type GaN, and the
10   cladding layer 302 of p-type AlGaN and the contact
layer 303 of p-type GaN are formed consecutively on
the contact layer 54 in correspondence to the stripe-
formed gap 301n of the mask pattern 301c, by
conducting the MOVPE process while using the mask 301A
15   as a mask. Simultaneously, an epitaxial layer 302A of
p-type AlGaN having a composition substantially
identical with the composition of the cladding layer
302 is formed outside the mask pattern 301c, and
another epitaxial layer 303A of p-type GaN having a
20   substantially identical composition with the
composition of the contact layer 303 is formed on the
epitaxial layer 302A. Thereby, the epitaxial
structure including the epitaxial layers 302A and 303A
is separated from the structure formed of the third
25   cladding layer 302 and the contact layer 303 by a
recess exposing the mask 301A.

     It should be noted that the epitaxial layer
303A is covered by another SiO_2 film 304, wherein the
SiO_2 film 304 includes an opening formed in
30   correspondence to the recess part so as to expose the
contact layer 303, and an electrode corresponding to
the electrode 62 is formed on the SiO_2 film 304 so as
to fill the foregoing recess. It should be noted that
the SiO_2 film 304 is formed to have a thickness of
35   about 200 nm by a high-temperature CVD process, and
the foregoing opening is formed in the SiO_2 film 304
by a wet etching process using HF.

1   As explained already, the laser diode 400 of
the present embodiment minimizes the formation of
particles on the mask 301A and the yield of production
of the laser diode is improved substantially. As the
5   laser diode 400 of FIG.13 allows the electrode 62 to
have a large area and a substantially flat top
surface, mounting process of the laser diode 400 is
facilitated substantially.

10   [FIFTH EMBODIMENT]
       As explained already, the selective growth
process used in the fabrication process of the laser
diode 300, 310 or 400 tends to cause the problem of
deposition of particles on the insulation mask. This
15   problem of particle formation becomes particularly
serious in the process of forming the cladding layer
302 of AlGaN. It should be noted that the AlN
component included in the AlGaN cladding layer 301 has
a tendency of preferential deposition on an SiO_2 film
20   that forms the mask 301, while the AlN component thus
deposited tend to act as a nucleus for formation of
the AlGaN cladding layer 301.
       In the experimental investigation that
constitutes the basis of the present invention, the
25   inventor of the present invention has discovered that
the formation of particles on an SiO_2 mask is
effectively suppressed in the selective growth process
of AlGaN conducted by an MOVPE process, by supplying
the gaseous source of the elements together with a gas
30   containing halogen.
       FIGS.14A - 14F explain the foregoing
experiments conducted by the inventor of the present
invention.
       Referring to FIG.14A, a 6H-SiC substrate 501
35   is cleaned in an organic solvent and then in water,
and the substrate 501 thus processed is then immersed
in a bath of HF for about 1 minute.

1   The substrate 501 thus processed is then
introduced into a reaction chamber of an MOVPE
apparatus so as to expose a (0001)Si surface thereof
on which the deposition of epitaxial layers is to be
5   made. After evacuating the reaction chamber, the
native oxide film is removed from the surface of the
SiC substrate 501 by processing the substrate 501 at
1080°C in a hydrogen atmosphere for about 5 minutes.
Next, the substrate temperature is reduced to about
10   1050°C, and an AlGaN film 502 is grown on the
foregoing (0001)Si surface of the substrate 501 while
supplying TMG, TMA and NH_3 with respective flow rates
of 44 µmol/min, 8 µmol/min and 0.1 µmol/min, together
with a carrier gas of H_2. The foregoing source gases
15   are applied directly to the substrate surface and the
AlGaN film 502 is grown thereon with a thickness of
about 1 µm.

Next, in the step of FIG.14B, the supply of
TMG and TMA is interrupted and the substrate
20   temperature is lowered to 600°C or lower while
continuously directing the NH_3 gas to the substrate.
Thereby, the atmosphere inside the reaction chamber is
changed to N_2. After cooling further to the room
temperature, the substrate 501 is taken out from the
25   deposition chamber, and an SiO_2 film 503 is formed on
the foregoing AlGaN film 502 with a thickness of 0.2
µm.

Next, in the step of FIG.14C, a resist film
is formed on the SiO_2 film 503, followed by a
30   patterning process to from a resist pattern 504 having
a width of 2 µm, such that the resist pattern 504 is
repeated with a pitch of 30 µm.

Next, in the step of FIG.14D, the SiO_2 film
is subjected to a wet etching process using HF as an
35   etchant to form a line and space pattern exposing the
AlGaN film 502. After removing the resist pattern 504
by using an organic solvent, the substrate 501 is

1   returned to the reaction chamber of the MOVPE
     apparatus. The reaction chamber is then evacuated,
     and the native oxide film is removed from the exposed
     part of the AlGaN film 502 by applying a heat
5   treatment process at 1050°C in H_2 atmosphere, while
     supplying NH_3. Further, a selective epitaxial growth
     of an AlGaN film 505 is made on the exposed surface of
     the AlGaN film 502 by supplying TMG, TMA, CH_3Cl and
     NH_3 with respective flow rates of 44 μmol/min, 8
10   μmol/min, 52 μmol/min and 0.1 μmol/min, together with
     a carrier gas of H_2.

     In the step of FIG.14F, the substrate
     temperature is then lowered to below 600°C while
     supplying NH_3 to the reaction chamber, such that the
15   atmosphere inside the reaction chamber is changed to
     the N_2 atmosphere. Thereafter, the substrate
     temperature is lowered to the room temperature.

     According to the selective growth process of
     the present embodiment, the CH_3Cl molecules supplied
20   in the step of FIG.14F to the reaction chamber
     together with the gaseous source material release Cl
     atoms as a result of the pyro-decomposition process
     thereof, wherein the Cl atoms thus released suppresses
     the AlN formation on the exposed surface of the AlGaN
25   film 502 by preferentially reacting with Al. The
     supply of CH_3Cl is preferably made to the reaction
     chamber by a gas inlet different from the inlet used
     for introducing a gaseous source of group V element
     such as NH_3. Thereby, the nuclei formation on the
30   SiO_2 mask 503 is impeded and the deposition of
     polycrystalline or particulate precipitates on the
     mask 503 is suppressed.

     It should be noted that the element that
     suppresses the AlN formation on the SiO_2 mask is by no
35   means limited to Cl but other halogen element such as
     F can be used also for the same purpose. Further, the
     compound that is used as the carrier of the halogen

1   atom is by no means limited to CH_3Cl but other halogen
compounds, including a metal-organic compound
containing halogen, may also be used.

    It should be noted that the selective

5   epitaxial growth process according to the present
embodiment is applicable not only to the fabrication
process of a ridge-type laser diode as described but
the present embodiment is also applicable to general
fabrication process of a semiconductor device that

10   includes a selective growth of a nitride film of a
group III element including Al.

[SIXTH EMBODIMENT]

    In the GaN-family laser diodes 100, 200,

15   300, 310 and 400 described heretofore, it should be
noted that there is formed an electron blocking layer
51 of AlN formed adjacent to the active layer
structure 40, wherein the electron blocking layer 51
is doped with Mg to a high concentration level and

20   blocks the electrons that are injected into the active
layer structure 40 and subsequently causing an
overflow from the active layer structure 40 as a
result of the large electric field formed in the p-
type epitaxial structure 50. For this purpose, the

25   electron blocking layer 51 is generally formed to have
a composition that provides a large bandgap. Thus,
the optical waveguide layer 52 of p-type GaN or the
cladding layer 53 of p-type AlGaN is formed above the
electron blocking layer 51. It should be noted that

30   the p-type AlGaN cladding layer 53 has a relatively
large resistivity, and because of this, the foregoing
large electric is created.

    FIG.15 shows the Mg concentration profile
used in the GaN-family laser diode disclosed in the

35   Japanese Laid-Open Patent Publication 10-56236 for the
part located above the active layer structure. It
should be noted that the GaN-family laser diode of

1   FIG.15 is formed on a sapphire substrate.

Referring to FIG.15, the laser diode
includes, in addition to the foregoing electron
blocking layer, an optical waveguide layer of GaN

5   formed thereon as a part of the SCH structure and a
cladding layer of AlGaN, wherein the electron blocking
layer, the optical waveguide layer and the cladding
layer are all doped with Mg to the concentration level
of about 5 x $10^{19}cm^{-3}$. Only the uppermost contact

10   layer of GaN is doped by Mg to the concentration level
of about 1 x $10^{20}cm^{-3}$. It should be noted that the
laser diode 100 of the previous embodiment also uses
the Mg profile of FIG.15.

On the other hand, the Mg concentration

15   profile of FIG.15 cannot avoid cracking in the
epitaxial layers used in nitride laser diodes. Such
cracks formed in the epitaxial layers provides
undesirable effect of decreased efficiency of laser
oscillation and increased threshold voltage. Thus, it

20   is desirable to reduce the crack formation as much as
possible.

In the experimental investigation on the
laser diode 100 described previously, the inventor of
the present invention has discovered that the cracks

25   formed in the epitaxial layers of the laser diode is
reduced substantially when the Mg concentration level
is reduced in the p-type GaN optical waveguide layer
52 and the p-type AlGaN cladding layer 53, all located
above the active layer structure 40.

30   Referring to FIG.16, it can be seen that the
crack density observed on the surface of the cladding
layer 53 is reduced sharply when the Mg concentration
level in the GaN optical waveguide layer 52 and the
AlGaN cladding layer 53 is reduced below the

35   conventionally used value of 5 x $10^{19}cm^{-3}$. When the
Mg concentration level is reduced below about 4 x
$10^{19}cm^{6-3}$, particularly below than about 3 x $10^{19}cm^{-3}$,

1   it can be seen that the observed crack density becomes substantially zero. In FIG.16, it should be noted that the vertical axis represents the crack density while the horizontal axis represents the Mg

5   concentration level.

In conformity with the crack density, the resistance of the laser diode 100 is reduced sharply when the Mg concentration level in the optical waveguide layer 52 and the cladding layer 53 is

10   reduced. Thereby, a minimum resistance is reached when the optical waveguide layer 52 and the cladding layer 53 have the Mg concentration level of $3 - 4 \times 10^{19} cm^{-3}$ as represented in FIG.17, wherein FIG.17 shows the Mg concentration level in the horizontal

15   axis and the drive voltage necessary for flowing a drive current of 100 mA in the vertical axis. With further decrease in the Mg content, it can be seen that the resistance of the laser diode 100 starts to increase again, while this effect is merely attributed

20   to the depletion of carries in the optical waveguide layer 52 and in the cladding layer 53 due to the excessively reduced concentration level of Mg.

FIG.18 shows the doping profile of Mg for the laser diode 100 of FIGS.6A and 6B optimized in

25   view of the discovery of the relationship of FIG.17.

Referring to FIG.18, the electron blocking layer 51 of p-type AlGaN has a composition of $Al_{0.18}Ga_{0.82}N$ and is formed on the active layer structure 40 with a thickness of about 20 nm, wherein

30   the electron blocking layer 51 is doped with Mg to the concentration level of about $1 \times 10^{20} cm^{-3}$. On the electron blocking layer 51, the optical waveguide layer 52 of p-type GaN is formed with a thickness of about 100 nm, wherein the optical waveguide layer 52

35   is doped with Mg to the concentration level of about $4 \times 10^{19} cm^{-3}$. Further, the cladding layer 53 of p-type AlGaN has a composition of $Al_{0.09}Ga_{0.91}N$ as noted

1   before wherein the cladding layer 53 is formed on the optical waveguide layer 52 with a thickness of about 550 nm. The cladding layer 53 is also doped with Mg to the concentration level of about $4 \times 10^{19} cm^{-3}$.

5   On the cladding layer 53, the contact layer 54 of p-type GaN is formed with a thickness of about 80 nm, wherein the contact layer 53 is doped with Mg to the concentration level of about $1.5 \times 10^{20} cm^{-3}$.

According to the present invention, the

10   crack density in the optical waveguide layer 52 and the cladding layer 53 is minimized by setting the Mg concentration level in the layers 52 and 53 to be about $4 \times 10^{19} cm^{-3}$ or less. Thereby, the resistance of the laser diode is minimized. Further, the

15   threshold voltage of the laser diode is decreased by increasing the Mg concentration level in the electron blocking layer 51 above the foregoing value of about 4 $\times 10^{19} cm^{-3}$. Further, the increase of the laser diode resistance as a result of the excessively low impurity

20   concentration level is also avoided.

FIG.19 shows a modification of the embodiment of FIG.18 in which the Mg concentration level in the optical waveguide layer 52 and the cladding layer 53 is decreased to about $3 \times 10^{19} cm^{-3}$

25   in view of the relationship of FIG.17. In the case of FIG.19, too, the crack density in the epitaxial layers constituting the laser diode 100 is reduced to substantially zero by combining the electron blocking layer 51 and the contact layer 54, which are doped to

30   a high concentration level. Thereby, the crack density, and hence the resistance, in the epitaxial layers is successfully minimized.

Further, the present invention is not limited to the embodiments described heretofore, but

35   various variations and modifications may be made without departing from the scope of the invention.

The present application is based on Japanese

1   priority applications No.10-135425 and 10-353241 filed
     respectively on May 18, 1998 and December 11, 9998,
     the entire contents of which are hereby incorporated
     by reference.

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